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Atomization Mechanism of Wall-Bounded Two-Phase Flows (Preprint)

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ABSTRACT

The current understanding of droplet generation processes from liquid films is reviewed. Films are defined as liquids with one free and one wall-bound surface. In many of the systems where films occur, atomization is an undesirable side-effect of the two-phase flow. The motivation for this study, however, is a process where atomization from the film is the goal—a gas-centered swirl coaxial rocket injector. Because atomization is often unwanted in film configurations, few studies focus on the mechanisms that cause atomization. The large body of literature on the atomization of jets and sheets is, therefore, utilized to develop an understanding of film atomization. Similarities and differences between the geometries are discussed as applicable. Generally, the atomization is considered to involve two steps: the creation of a disturbance on the film surface and the breakdown of this disturbance into droplets. Prompt Atomization, where atomization occurs directly at a nozzle exit, is also briefly considered. Several atomization mechanisms are identified and qualitatively described.

INTRODUCTION

The physical processes that lead to the disintegration of a liquid or the formation of droplets from its surface are termed atomization mechanisms. Atomization occurs due to the complex interaction of several forces: aerodynamic, viscous, surface tension and inertial, for example. The absolute and relative values of these forces determine the mechanisms involved. Knowledge of the mechanisms allows the development of a quantitative description of the atomization—droplet size, distribution and velocity, for example. In reality, however, uncertainties remain in both qualitative and quantitative descriptions of mechanisms as well as in their range of applicability. Nevertheless, a knowledge of the operable atomization mechanism(s) is important as it implies qualitative aspects of the resulting spray and suggests relevant scaling parameters and design methodologies. Scaling is particularly important in some atomization applications, such as rocket engines, where full-scale tests at operational pressures and/or temperatures can be costly and difficult. A solid understanding of the physics involved in the breakup process, therefore, helps to focus experiments and ground correlations as well as directing the development of new atomizer concepts.

The main aim of this work is to develop a better understanding of film atomization mechanisms, particularly those in rocket injectors. The motivations for this work are the recent studies of a gas-centered swirl coaxial rocket injector (Fig. 1) where atomization occurs from an annular film^{1,2}. The bulk of atomizer literature deals with jets or sheets as the majority of atomizers utilize these configurations. Here a jet is a column of liquid with a free surface, a sheet is a stream of liquid with two free surfaces and a film is a liquid with one free and one wall-bound surface (Fig. 2). Comparatively little research exists on atomization mechanisms in the film configuration. Consequently, the summary of film atomization mechanisms will be predicated on brief reviews of the basic atomization regimes of jets and sheets. The similarities and differences between atomization in the geometries will be emphasized. The following section covers generalized atomization regimes which are used to set the stage for the subsequent discussion of specific

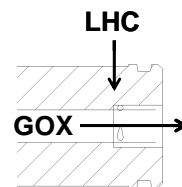


Figure 1: Gas-centered swirl coaxial injector

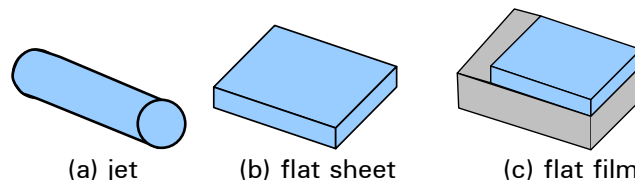


Figure 2: Potential liquid configurations.

atomization mechanisms and submechanisms. Due to space constraints only qualitative descriptions are given. The complexity of mechanisms and subsequent incompleteness of descriptions available in the literature lead to two focuses in this paper: reviewing existent theories and literature plus encouraging and directing future research in this area.

GENERALIZED ATOMIZATION REGIMES

The lack of extensive literature regarding film atomization at rocket injector conditions necessitates utilizing the similarities between film atomization and the breakup of jets and sheets. To highlight and gain an understanding of the basic similarities between the geometries, this section compares the general atomization regimes of the three geometries. These regimes are highly simplified dealing with the basic character of the atomization. The predominance of film atomization literature deals with a single atomization regime, but similarities between geometries point to the existence of other regimes.

A review of the literature on jets exiting into quiescent and coflowing environments reveals three main atomization regimes: Rayleigh³, Surface Breakup⁴ and Prompt Atomization⁵ modes. The first regime, the Rayleigh mode, results from surface-tension-driven instabilities which cause the entire column's surface to undulate eventually producing a stream of large droplets (and possibly small satellite droplets) downstream³. In the Surface Breakup mode droplets are formed from disturbances⁴, e.g. waves or ligaments, throughout the surface of the jet. The Prompt Atomization mode is characterized by the disintegration of the jet immediately after its exit from the injector⁵. More information on the jet geometry can be found in the influential book by Lefebvre⁶ or the review articles of Lasheras and Hopfinger⁴ (jets in coflow), Margason⁷ (jets in cross-flow) and Sallam, Dai and Faeth⁸ (turbulent jets). Jets in cross-flow have not been considered here as this configuration cannot exist in a film geometry. Turbulent jets exiting into quiescent atmospheres exhibit turbulence enhanced Rayleigh and Surface Breakup modes as well as a mode where the entire jet is displaced with the subsequent breakup occurring through modes similar to jets in cross-flow⁸.

A review of sheet literature suggests generalization into four atomization regimes⁹⁻¹³: Sheet Pinching, Surface Breakup, Perforated and Prompt Atomization. Sheet Pinching resembles the Rayleigh mode in that hydrodynamic instabilities cause the entire downstream edge of the liquid to separate from the bulk sheet. In Sheet Pinching this separation produces a ligament whose length is the sheet width; this ligament then breaks up into droplets due to Rayleigh breakup¹⁴⁻¹⁶. The drivers of the instabilities are different in jets and sheets, however. The Rayleigh mode is driven by surface tension³ while Sheet Pinching is generally the result of aerodynamic or viscous forces, especially at the Weber numbers found in rocket injectors¹⁷. The Surface Breakup and Prompt Atomization modes are also similar to the same-named regimes in jets. In the Surface Breakup regime droplets are produced from disturbances on the liquid surface^{12, 18, 19}. Note that, in generalizing regimes, this Surface Breakup mode also encompasses the rim-shedding regime mentioned throughout sheet literature^{18, 19}; in other words, the disturbances may not exist over the entire sheet but only in one location. In the Prompt Atomization regime disintegration of the sheet occurs immediately after its exit from the injector^{9, 19}. Finally, the Perforated regime is characterized by holes that grow and induce breakup¹⁰. The reader is directed elsewhere for a more in-depth review of sheet atomization, e.g. Lefebvre's book on atomization⁶ or the review paper by Sirignano and Mehring²⁰. Similar to the abbreviation of the jet section, nonparallel (impinging) flows were not considered here. This decision was made because 1) there is little work in the subject of sheet breakup due to air impingement, 2) the mechanisms involved in nonparallel sheet atomization are found to be substantially different²¹ and 3) much remains unknown for the case of parallel flow without adding this further complication.

The literature of film atomization focuses on a single atomization regime—Surface Breakup. The above review of jet and sheet atomization suggests the possibility of other regimes, however. Three further regimes seem possible: a mode in which the downstream edge separates from the main body of fluid, a mode related to perforations and a Prompt Atomization mode. Further examination reveals the first two to be somewhat unlikely in films. In this geometry the fluid is in contact with a wall where surface forces oppose the growth of holes and exclude the possibility of Rayleigh breakup or created "ligaments". However, the breakup of a wall-bounded ligament, or ribbon, could differ substantially from the breakup of the entire film due to marked differences in shape and velocity profiles and, therefore, warrants future investigation. Because the formation of the wall-bounded ligament is not really Sheet Pinching, this potential regime will be titled Ribbon Forming in order to clearly separate the regime in the two geometries. Perforations in the film have been shown to cause streamwise ribbons²² and may potentially

lead to atomization, so that a Perforated regime cannot be ruled out. Finally, if the film is sheltered prior to its introduction as a film it may undergo Prompt Atomization, i.e. disintegration immediately after its introduction. As with the sheet and jet, only flows that are, in the mean, parallel are considered here. Reasons for this abridgement include a lack of literature on the subject of impinging air flows and the large amount of information, known and unknown, regarding the parallel configuration.

An additional complexity of sheets and films should be discussed prior to an examination of breakup mechanisms—different geometries are possible, mainly flat and annular. Many of the breakup phenomena are similar, but annular sheets have some additional complexities in the ability to impart swirl to the gas and/or liquid flow. This swirl can change the evolution of the sheet or film, particularly the development and growth of waves on its surface¹³, but the atomization regimes and general mechanisms responsible for droplet formation do not appear to change. Additionally, the curvature of the sheet/film in the annular geometry can enhance the growth of waves on the liquid's surface¹⁷. As far as possible this paper is a general look at film atomization applying to either configuration.

ATOMIZATION MECHANISMS

Following the generalization into atomization regimes, film breakup can be further simplified into two types of processes. In the Surface Breakup, Ribbon Forming and Perforated regimes atomization occurs through the formation of a disturbance followed by the breakdown of this disturbance into droplets. In the Prompt Atomization regime, atomization is considered to occur “instantly” with no intermediate disturbance formation and growth. This section opens with a discussion of mechanisms leading to disturbance creation. A discussion of disturbance breakdown mechanisms follows. Then Prompt Atomization mechanisms are discussed. Finally, an additional mechanism, film separation, is presented; this mechanism does not easily fit into the above classifications.

DISTURBANCE CREATION

The disturbances discussed here are waves, ligaments and perforations. Bubbles and impacting droplets are other possible types of disturbances, but discussion of these is left to the breakdown section. Waves can occur over the entire surface, or they can be localized three-dimensional structures. They are generally wider than they are high. Ligaments are localized protrusions and, generally, have lengths that exceed their widths. Perforations are breaks in the sheet or film, holes, which are shaped as a closed circle/oval or as an open seemingly-parabolic shape.

Liquid Turbulence

Experiments in jet, annular sheet and exterior annular film configurations show that atomization dynamics due to liquid turbulence are similar in all three configurations²³. Turbulent eddies in the liquid interact with the interface forming surface disturbances. Sarpkaya and Merrill²⁴ give an in-depth description of the eddy dynamics; Faeth and coworkers^{12, 25} present a simplified quantitative model of ligament formation. Their model assumes that the ligament size is related to the size of the eddy which interacts with the interface. The smallest ligaments are caused by the smallest eddies with sufficient kinetic energy to overcome the surface energy of the liquid or those based on the Kolmogorov length scale, whichever are larger. Viscous dissipation of the turbulent energy causes smaller and fewer ligaments to be formed as the distance from the liquid-air contact point increases^{12, 25}. Experiments on flat films show that, contrary to expectations, any roughness on the wall surface immediately disturbs the entire film and has a marked effect on ligament formation and droplet production²⁴. These findings indicate that roughness must be accounted for to achieve accurate quantitative descriptions.

In addition to this eddy-interaction mechanism, recent work by Lioumbas et al.²⁶ suggests that the transition from laminar to turbulent flow may initiate solitary waves in film flows. They define solitary waves as waves with large amplitudes and relatively long wavelengths. Their findings are for inclined, stratified pipe flows with and without parallel gas flow, but the findings are similar to those for free falling films²⁶. The intermittent way in which flow transitions from laminar to turbulent is suggested as a reason for the intermittency of the solitary waves, which are separated by relatively large stretches of smooth, flat film²⁶. In rocket injectors the film exists for only a short length, but if the flow was near transition upon the film's introduction then these waves might form and play a role in atomization. Other annular flow work has shown that solitary waves may cause atomization in otherwise unatomizing flows²⁷.

Hydrodynamic Instabilities

Hydrodynamic instabilities lead to the formation and growth of waves at the interface between the liquid and gas. Both the cause and the quantitative description (wavelength, growth rate, etc.) of these instabilities are important. Instability analyses are common in both sheet and film atomization studies. Theoretical investigations into the aerodynamic instabilities of flat sheets began more than fifty years ago; seminal works in this geometry include those by Squire²⁸, York et al.²⁹, Hagerty and Shea³⁰, Dombrowski and Johns¹⁴ and Li and Tankin³¹ among others. Most of the instability modes of films are the same as those found in sheets, although film instability analysis has its own seminal works (³²⁻³⁵, for example). Differences due to the movement of only one interface in the film versus two in the sheet play little role in the stability of the film but do effect further breakup of the liquid. Differences in boundary layer profiles between the two geometries are important, however.

Commonly considered driving forces include aerodynamic shear, air turbulence and/or viscous stratification³⁶. Surface tension is a common driver for jets, but generally stabilizing for sheets and films¹⁷. A thorough theoretical investigation by Boomkamp and Miesen³⁶ examines several instability sources in depth and classifies instabilities in infinitely deep films. Kelvin-Helmholtz¹⁷, instabilities driven by aerodynamic shear, and Tollmein-Schlichting³⁷ instabilities, driven by gas turbulence, are the ones most often emphasized in film analysis. Interestingly, Boomkamp and Miesen³⁶ conclude that Kelvin-Helmholtz waves do not exist in viscous flows—the introduction of “viscosity effects, however small, into the stability problem rules out the possibility of the essentially inviscid Kelvin-Helmholtz instability”. As with jets and sheets, analysis of infinitely deep films has observed that velocity profiles, particularly boundary layer profiles play an important role in determining the instabilities of a system^{38, 39}. In particular, gas-phase profiles, which are often neglected, can be important^{38, 39}. Unfortunately, exact velocity profiles are often unknown and are difficult to predict or measure. Swirl in the gas and liquid phase affects the stability of annular sheets¹³ and is likely to also affect annular films.

The large body of work on sheet instabilities helps highlight the complexities of developing accurate descriptions. For example, analyses often focus on temporal instabilities²⁰, where the growth rate is considered a function of time. In actuality, the problem is a tempo-spatial one, but these equations are quite complex and difficult to solve. Continued debate exists over the appropriateness of solely temporal or spatial formulations^{3, 19}. To further complicate this debate recent numerical studies suggest that the short-time growth of wavelengths which are stable at long times is important⁴⁰; this line of investigation has predicted streamwise ligaments, which the classic analyses have difficulties predicting⁴¹. Another example of uncertainty exists in the use of linearized equations. Most analyses are linear due to the complexity of the full nonlinear formulations. To linearize the equations one must assume that the disturbances remain small; in atomization processes this assumption is often questionable at best^{28, 29, 42}. Hydrodynamic instabilities theories focus on a most unstable wavelength, the one with the fastest (shortest) growth rate, and suggest that the droplet size is proportional to this wavelength. This assumption has been successfully used to aid the generation of empirical correlations for film atomization in cooling tubes⁴³. However, recent numerical work by Li et al.⁴⁴ shows that different droplet diameters can be generated from the same disturbances (including the same wavelength). These findings may suggest a weakness in stability analyses, but more likely highlight the limited understanding of wave breakdown mechanics. Likely, properties of the instability other than wavelength are important, e.g. amplitude and/or evolution time.

Some experimental corroboration for the simplified theories does exist, however. Wavelengths have been measured and compared to predictions. Application of the theory can be difficult, however, due to a limited knowledge of the flow parameters in the nozzle and film; theories may require the pressure drop across the nozzle, the shear layer thickness or other parameters not easily measured or predicted. Also, only one wavelength out of the spectrum of unstable waves is measured. This is generally assumed to be the most unstable wavelength. Despite these complexities, experimental comparisons have been favorable^{43, 45}. For further reading on the subject of instabilities in films the work of Boomkamp and Miesen³⁶, Ostrach and Koestel⁴⁶ and the notable text of Drazin and Reid⁴⁷ are recommended in addition to the seminal works listed above.

Vortices in the Gas Phase

As with liquid turbulence, eddies in the gas may contact and deform the interface. To do this the structures must possess enough energy to overcome the surface, potential and inertial energy of the liquid at the interface. Eddies may have indirect effects as well, such as changing the hydrodynamic

instabilities of the system³⁶ or increasing the aerodynamic growth of waves⁴⁸. In addition to structures formed by turbulence, vortices may form in the gas due to flow separation around the injector hardware or over the roughened liquid surface. Compared to liquid turbulence and hydrodynamic instabilities, little atomization literature exists in which direct gas-phase interactions with the coherent liquid are considered. This lack of literature is likely due to the low energy of gas eddies in most applications due to the low density of the gas; it has been shown that aerodynamic effects on jets can be neglected if the liquid-to-gas density ratio is above 500^{12, 25}. In rocket injectors, however, gas densities and eddy energies may be large. Experiments by Lozano et al.⁴⁹ found gas vortices may be important even at atmospheric pressures. They found gas flow separation and its subsequent vortices, as well as vortices formed at the nozzle, helped force flapping of a liquid sheet. Film work by Jurman and McCready⁴⁵ suggests that air turbulence helps cause distortions and waves, but no specific mechanism is given.

Recent work includes a planned investigation of the effect of vortices created by a backward-facing step on a liquid film⁵⁰. This work was motivated by a gas-centered swirl coaxial injector similar to the one that motivated this review article^{1, 2}. The single-phase work observed both stationary and shed vortices⁵⁰. A vortex near the liquid injection point might in essence constrict the flow of the film passing under it. This constriction would accelerate the flow; additionally, a thicker area of film could be created just upstream or downstream of the vortex due to the constriction. The vortex would also change the gas flow downstream of itself leading to different aerodynamic forces. All of these would affect the subsequent behavior of the film possibly causing disturbances or their growth, but would not directly cause atomization. A direct atomization mechanism caused by strong vortices can be hypothesized, however. As an example, consider the mechanism illustrated in Fig. 3 where the gas contains a clockwise-rotating vortex in a bulk flow (from left to right). This vortex could force the film to thin in the downstream direction and drag fluid up along its upstream edge causing a wave or ligament to form. Further, if the vortex was strong enough, it could thin a portion of the fluid enough or drag the fluid with enough force to cause separation from the main flow. This mechanism may explain numerical simulation findings of “large perturbations of the gas-liquid interface with a wavelength similar in size to the scale of the large, energy containing eddies”⁵¹. No definitive evidence of this “scooping” mechanism has yet been reported, but the numerical results of Li et al.⁴⁴ show liquid behavior consistent with such a mechanism, especially their results where the liquid and gas were the same fluid (no surface tension).

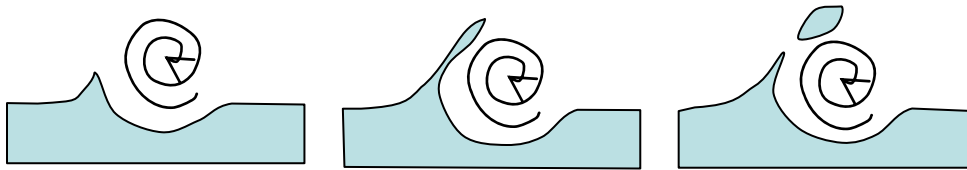


Figure 3: Possible progression of a “scooping” mechanism.

Pressure Fluctuations

Pressure fluctuations may be caused by cavitation, feedback from the environment (from combustion instabilities, for example) or feedback due to the atomization process itself. All of these causes are difficult to predict and model accurately. Pressure fluctuations cause disturbances mainly by altering the velocities in the chamber and the supply rate of the liquid and/or gas. They may also cause impact waves as observed for impinging jets⁵². Disturbance creation via pressure fluctuation has received almost no attention.

Mass-flow changes can lead to localized changes in liquid thickness, e.g. a “bulge” following a dip in gas pressure or spike in liquid supply rate. Experimental studies of annular films have demonstrated that such pulses of fluid can lead to atomization, even in flows that would otherwise not atomize²⁷. Additionally, these mass-flow changes alter the fuel and/or gas velocity and, therefore, many of the fundamental characteristics of the flow. In rocket engines pressure fluctuations are almost always accompanied by velocity fluctuations. These disturbed velocities can, in turn, cause hydrodynamic instabilities, transitions to turbulence or other disturbance creation or breakdown events. In impinging jets waves are generated by pressure or momentum fluxes in either or both jets⁵²; these impact waves may be present in a film configuration where a jet impinges on a wall. Available literature on atomizers that utilize jets impinging with walls do not report these impact waves, however⁵³.

Another effect of pressure is found for annular sheets and can be indirectly compared with flows that change from nearly slug to annular flow. Adzic et al.⁹ have observed several subregimes driven by a cyclic buildup of pressure in the interior hollow of an annular sheet. The cylindrical sheet closes downstream due to surface tension forces thus trapping the interior air. The additional air fed to the system increases the pressure inside the “bubble”. Eventually, pressure and surface tension cause this bubble to seal and separate from the rest of the sheet⁹. This mechanism cannot directly occur in annular films, but a cyclic buildup of pressure may result from flow changes from nearly slug to annular flow which may, in turn, drive other disturbance-causing events.

Perforation Causes

Perforations in films differ from those in sheets due to the interaction of the liquid and the wall. Wetting of the wall creates a surface tension force opposing the growth of the hole, slowing or stopping it²²; indeed, film perforations may close or grow²² while holes in sheets always expand¹⁰. Quiescent and flowing films may “spontaneously” form holes, likely due to surface imperfections or forces at the molecular level^{22, 54}. No specific mention of perforation causes is found in the film-atomization literature. Several causes have been suggested in the sheet literature, however, which may apply to films. Stapper et al.¹⁸ suggest holes are formed due to thinning in the streamwise direction as a reaction to streamwise vortices. Fraser et al.¹⁰ suggests some other causes including solids or bubbles in the liquid, droplet impingement or ripples. After various experiments they conclude that solids, bubbles and droplet interactions are not the cause of their perforations¹⁰. Due to the ripples found with the perforations, hydrodynamic instabilities have also been suggested as a possible cause of perforations²⁹.

Perforation growth is unlikely to prove important in most rocket injectors until the later stages when the film has thinned substantially. By this point the bulk of the atomization properties have been defined by the previous breakup of the bulk of the film. This mechanism may be important, however, if the film is initially quite thin or if the atomized liquid barely wets the nozzle material (as in some liquid metal or polymer atomization processes).

DISTURBANCE BREAKDOWN

For atomization to occur a disturbance must evolve into droplets. The breakdown process requires a finite time and often a minimum disturbance size, so that not all disturbed surfaces produce droplets. The following discussion is partitioned based on the type of disturbance which creates the droplet(s) despite some overlap of breakdown mechanisms between the disturbance types. Also discussed here is atomization due to the interaction of “particles”, i.e. droplets or bubbles, with the surface.

Wave Breakdown

Waves may maintain their height, shrink or grow. Height decreases are generally due to energy losses such as viscous diffusion⁵⁵; growth is due to aerodynamic enhancement, coalescence of waves or additional wave production events^{19, 41, 56}. Most often wave growth due to aerodynamic enhancement is considered, although vertically upward annular flow studies have shown coalescence can be important⁵⁶. Knowing the height of the wave is important for determining if and where breakdown occurs. Here several breakdown possibilities are considered: stripping from the wave crest, wave breaking (as on a beach), “bag breakup”, wave splitting or localized growth followed by ligament breakdown and breakdown following Ribbon Forming. Because stripping occurs in both waves and ligaments it is dealt with in the Ligament Breakdown section below.

Complex three-dimensional gas and/or liquid vortices may cause a single wave or the edge of a sheet to split into multiples waves or ligaments. This splitting has been observed by Stapper et al.¹⁸ Other perforation causes may act locally on a wave to cause splitting. Similarly, perforations may split the bulk of the film causing ribbons to form²². Theories detail the growth and stability of these ribbons, but consider flow rates much smaller than those typical of rocket injectors²². Ribbon formation has also been observed on the surface of rotating cups and disks and a theory exists to calculate their formation⁵⁷, but this splitting only occurs in nonwetting fluid-solid combinations. Split waves continue to evolve as smaller waves or ligaments and may eventually breakdown into droplets; ribbons alter the gas and/or liquid flow and may evolve as detailed in the Perforation Evolution section below. Instead of splitting the wave may experience localized growth which transforms it to a ligament. One such example would be the interaction of vorticity with the surface, similar to that found in the numerical experiments of Li et al.⁴⁴ but localized. Once a wave transforms to a ligament other mechanisms may cause droplets to be produced.

Growth of a wave to the extent that the trough meets the wall, forming a ribbon is another breakdown possibility. In sheets, a long ligament like this would breakup via Rayleigh's mechanism¹³, but in films this mechanism is not active because the ligament is wall-bounded. The additional force due to aerodynamic flow over the curved ribbon might cause a section of the ribbon to detach from the wall. This detached ligament could breakup via Rayleigh's mechanism. In a more wetting fluid, i.e. one with greater surface-tension forces, the additional aerodynamic force would likely change the shape of the ribbon only, creating a higher, narrower segment. This segment might undergo wave breaking, stripping, splitting, bag breakup or remain coherent.

Growing waves may reach a size where they are not self-supporting causing them to break, as waves do on a beach. Small wavelength waves (<2mm) evolve into spilling breakers while larger waves become plunging breakers⁵⁵. Spilling breakers would be expected in atomizers and are characterized by a capillary-gravity "bulge" at the top front of the wave which leads to turbulence on the downstream side of the wave⁵⁵. This turbulence could generate ligaments (and bubbles) as discussed elsewhere. Plunging breakers are more energetic than spilling breakers and create a jet which plunges into the film ahead of the wave⁵⁵. This plunging jet may create droplets via a splashing mechanism⁵⁸. A similar mode of droplet creation is observed in turbulent films, but creates only small numbers of relatively small droplets^{24, 59}. These results are backed up by numerical models of plunging breakers⁵⁸. Both types of breakers entrain air which may lead to atomization^{55, 58, 59}; however, as discussed later bubble rupture creates a fine spray and a few larger droplets so that many bubbles would need to burst to create appreciable atomization. All of these findings suggest wave breaking is of secondary importance. An additional indication of this is the suggestion by wave stripping theories that few waves would progress to breaking conditions because of mass loss due to stripping.

"Bag breakup" results from a mechanism that initially resembles wave breaking and later resembles bag breakup in droplets²⁷. This process is one of the few that has been experimentally observed for film flow, in particular vertically upward annular flow²⁷. Here the wave is undercut due to liquid or gas eddies at its base causing the formation of a thick top rim with a thin bridge connecting it to the bulk liquid. The rim may collapse toward the liquid while the bridge stretches due to air entrainment forming an open pocket which grows to some critical point after which it catastrophically fails. This failure produces small droplets and a thick rim at the pocket's leading edge²⁷. The rim devolves into droplets via a Rayleigh mechanism²⁷. Woodmansee and Hanratty⁶⁰ also report a similar mode of atomization for flat films. They observe a secondary wave which accelerates and partially separates from the film forming a thick ligament. This ligament is stretched and thinned and eventually devolves into droplets. Because of their under-film imaging and the relative thinness of the bag it is possible that the observed ligaments actually had attached thin films indicating bag breakup.

Ligament Breakdown

Numerous mechanisms can cause ligaments to evolve into droplets. These mechanisms include stripping, as briefly mentioned above. Droplets can also be formed by the Rayleigh mechanism or by liquid turbulence which cuts them off at their base. Another, less explored, possibility parallels the idea of fragile shattering of droplets as described by Khavkin⁶¹ where viscous droplets subjected to deforming forces behave as solids.

The Rayleigh mechanism for droplet creation from ligaments is the same as that responsible for the breakup of low-speed jets. Instabilities driven by surface tension cause the oscillation of the ligament surface and, eventually, the creation of a droplet⁶. This mechanism has been observed and described in several investigations of atomization due to liquid turbulence^{24, 25}. Rayleigh's theory predicts the creation of droplet 1.89 times the diameter of the jet; experiments indicate that droplets created from turbulent liquid film flow are slightly smaller, but on the same order of these predictions²⁴.

Ligament/wave stripping is one of the most commonly considered causes of droplet formation from a film. Gas strips a mass of liquid from the tip of a wave or ligament once certain conditions are met. The quantitative application of this mechanism is hindered by a number of factors, but comparisons of semi-analytic derivations with experimental results show promise^{2, 46, 62}. Application of theories is difficult due to a lack of knowledge and predictive capability of certain flow parameters, for example the distribution of wave/ligament sizes and relative velocities. Even the development of theories can be difficult due to uncertainties about when (i.e., at what disturbance height) and how much liquid is sheared from the film. Holowach et al.⁶² suggest that the maximum amount of lost liquid occurs when the forces on the distorted wave tip are evenly balanced; Mayer⁶³ assumes waves break off when the amplitude of the wave equals

its wavelength; Woodmansee and Hanratty⁶⁰ observes that secondary waves separate from the main wave due to variations in air pressure induced by the flow over the waves. The actual situation is a range of probabilities that stripping will occur where the likelihood increases with the disturbance amplitude and relative velocity between the gas and liquid. Another difficulty in developing theories is the uncertainty in wave shape which affects the aerodynamic and surface forces on the wave. Azzopardi²⁷ observes a stripping mechanism in annular flow. A very large percentage of the ligament is lost, however, so that the liquid turbulence mechanism of the next paragraph cannot be ruled out based on the limited amount of information available.

Experiments studying turbulent flat films found that some ligaments detach from the sheet at their base²⁴. The investigators hypothesized that turbulent eddies at the base of the ligaments caused them to separate from the bulk fluid²⁴. These and other studies suggest that most ligaments, about 90%, breakdown due to the Rayleigh mechanism and about 10% undergo this separation^{24, 25}. These studies are with water in quiescent air and may change for different liquid-gas combinations or with imposed flow. The droplets produced via this mechanism are much larger than those created by the Rayleigh mechanism. Droplet size could be predicted if the diameter and length of the ligament was known. No exact prediction of when and where this separation will occur can be given, but it may be possible to deal with the location and frequency of shedding stochastically.

Fragile shattering occurs when the liquid is unable to react (by deforming) to the surrounding flow because the speed of deformation exceeds the speed of liquid molecule relaxation. Because the fluid is unable to relax quickly enough it acts, essentially, as a solid. Khavkin's⁶¹ development of this theory involves secondary droplet breakup in pressure-swirl atomizers. Here the droplets are subjected to uneven force loading due to the centripetal forces, which acted to deform the droplets. A sufficiently large viscosity delays relaxation causing the liquid to react like a solid and shatter⁶¹. Ligaments subjected to swirl, sudden velocity changes or other velocity fields that vary along their lengths could also undergo shattering if their viscosity and the forces deforming them were large enough. At this time, however, the existence of this mechanism remains speculation.

Perforation Evolution

Film literature involving perforations reports only attached "droplets" and then only for the case with no gas or liquid flow⁵⁴. A thick rim, containing the liquid which used to occupy the hole, is formed around stationary and expanding holes²². Air-borne droplets may be created from the collision of these rims, as they are in sheets¹⁰, but this mechanism has not been reported in the literature. Possibly, the smaller growth rate of film holes results in collisions with insufficient force to generate droplets. Still, film perforations could be important because they alter the gas flow over the film and, consequently, change the drivers for disturbance creation and growth. For example, the thickened rim along the edge of a hole would accelerate the flow over the rim. This acceleration could separate part of the rim from the wall or bulk film resulting in bag breakup or Rayleigh breakup as detailed above. Alternately, mass could be stripped from the rim's surface.

"Particle" Interaction

Two-phase flows have two types of discrete objects that may interact with the interface: droplets and bubbles. Droplets formed by other atomization mechanisms may later impact the film and create secondary droplets. Similarly, bubbles, trapped during droplet collisions or waves breaking, may rise to the surface and rupture creating droplets. The main focus of droplet impingement work has been on heat transfer or removal of droplets from the gas. Bubble studies generally examine single bubbles in quiescent or slow-moving films, not rocket injector conditions. Indeed, neither mechanism appears to be important in rocket injector atomization.

Droplet collision with a film is an active subject of its own. Atomization studies are somewhat limited, however, with consideration generally given to the impact of a single droplet where the creation of the colliding droplet and the behavior of the ejected droplets are given little or no consideration. Perhaps earlier findings that splashing was of less importance than other droplet creation mechanisms in flat film flows are responsible for this lack⁶⁰. Colliding droplets may bounce, merge or create secondary droplets⁶⁴. Droplet creation may occur through partial absorption, corona splashing or prompt splashing^{64, 65}. Partial absorption occurs when the colliding droplet merges with the film and subsequently creates a single, wide projection that may produce a single droplet⁶⁴. Corona or crown splashing creates a thin liquid sheet which spreads radially outward and may break into fingers and then into droplets⁶⁵. This type

of splashing is often photographed. Prompt splashing, like prompt atomization, takes place immediately after impact without any observable sheet or jet⁶⁵. Splashing is unlikely to be an important droplet creation mechanism in atomizers where the goal is the transformation of the entire film to droplets. To be important a large percentage of the atomized mass would have to come from impacts. Since created droplets are smaller than the impinging droplet this condition requires the bulk of the initially created droplets to impact the film. Additionally, atomization through splashing cannot be self-sustaining—eventually created droplets will be too small (and/or too slow) to produce new droplets. Another reason splashing is unlikely to be important in rocket injectors is that the film exists for a relatively short distance limiting the number of possible collision events.

Entrainment of air, precipitation of gas or vapor bubble formation (cavitation or boiling) may produce gas bubbles. Lefebvre⁶ discusses taking advantage of dissolved gases and/or boiling in a section on effervescent atomization, a term which is now used differently. Chen et al.⁵⁸ and Rodríguez et al.⁶⁶ discuss gas entrainment due to breaking waves, Rein⁵⁹ mentions other processes that lead to air entrainment (e.g., droplet collision with the film and jet plunging) and Woodmansee and Hanratty⁶⁰ mention air entrainment due to an interaction of ligaments and waves. Gas bubbles rise through the film and contact the gas-liquid interface. Droplets and, possibly, a ligament are created when these bubbles burst. Rupture of the thin film separating the bubble and the bulk gas produces film droplets. Film droplets are very small, on the order of a few microns⁶⁷. When the collapse of a bubble produces a ligament jet droplets may be formed. Jet droplets are tens to hundreds of microns in diameter⁶⁷. Bubbles must be below a critical size for their collapse to produce a ligament that devolves into one or more droplets⁶⁸. Generally the jet is assumed to breakdown due to Rayleigh instabilities, but in principle could be fragmented by the other processes for ligament breakdown described above.

PROMPT ATOMIZATION MECHANISMS

If the liquid is initially sheltered, a Prompt Atomization regime might exist where disintegration occurs immediately after the liquid contacts the gas. Despite the instantaneous nature of the atomization needed in order to fall into this realm, Reitz and Bracco⁵, who studied this regime in jets, note that there may be some undetectable small intact length on which disturbances evolve and lead to atomization. This assertion helps to explain some of their results but remains unverified. No film literature exists, but jet breakup in this regime has been attributed to velocity profile relaxation, acceleration in the boundary layers, cavitation, liquid turbulence and aerodynamic effects. Experimental results indicated that no single mechanism could explain all of the behavior in this regime⁵. Due to the complexities of studying this regime, these are only the most-discussed set of possibilities, not an exhaustive list.

Velocity profile relaxation causes atomization due to the perpendicular velocities present in the liquid or caused by its change from confinement to free⁵. This relaxation is likely to be less disruptive in a film arrangement than in jets or sheets due to the existence of a wall-bound surface. Similarly, boundary layer relaxation/acceleration is less likely to be important in films than in other geometries. Here disintegration is due to the changes in tangential stress at the interface and instabilities associated with the sudden change in boundary conditions⁵. If there is an intact surface than this relaxation could be important as studies have suggested that boundary layer relaxation may affect instabilities. Cavitation, liquid turbulence and aerodynamics effects are also known to have an effect on intact lengths of jets or sheets and have been dealt with above. Cavitation and aerodynamic effects help to explain a large part of jet behavior in the Prompt Atomization regime⁵.

Work by Khavkin¹¹ relates the droplet size produced in this regime back to the Kolmogorov length scale for turbulence. His idea is illustrated by a comparison with the breakdown of turbulent structures where intensive mixing inside the atomizer is equivalent to turbulent diffusion with particles changing their size and location instead of vortices. Particles divide until they reach a stable size determined by viscosity, i.e. the Kolmogorov length scale. A theoretical description of the resultant droplet sizes is formulated, but exact details on the formation of the particles are not given¹¹. Recent experimental studies observed a large amount of atomization occurring within gas-centered swirl coaxial atomizers in a location where the fluid is a film^{2, 51}. This internal breakup mode means there is little or no intact sheet at the injector exit, but it can only occur if the liquid and gas are in contact prior to exiting the nozzle. Clearly, this mechanism is not truly Prompt Atomization although certain studies may cause it to appear as such.

FILM SEPARATION

A final mechanism, which is unique to films, is separation from the wall due to a corner. As a film flows (or tries to flow) around a corner there is an adverse acceleration relative to the density stratification. This acceleration can cause the film to separate from the wall. When this happens atomization can occur through two mechanisms. Either the separation causes a ligament to form, similar to the Sheet Pinching mechanism, or the film becomes a sheet and breaks up from the sheet geometry. Maroteaux et al.⁶⁹ considered the production of Rayleigh-Taylor instabilities due to the adverse pressure gradient and postulated breakup would occur if the instabilities were above an empirical value. If the wave is larger than this critical value then a ligament will separate from the corner along the trough of the wave creating a long ligament which will subsequently breakdown via a Rayleigh mechanism⁶⁹. Alternatively, the liquid may remain intact for a short distance after separating from the wall. Further breakup would correspond to sheet atomization. Wang et al.⁷⁰ presents several predictions of the conditions under which this separation will occur.

CONCLUSIONS

Atomization is a complex process that occurs over a wide range of geometries and conditions. Film atomization has been generalized into four possible regimes (Surface Breakup, Ribbon Forming, Perforated and Prompt Atomization) after an examination of the atomization regimes of jets and sheets. These regimes have been further simplified into two classes Prompt Atomization and a class where disturbances are created, grow and evolve into droplets. Several causes of disturbances and their breakdown have been considered along with "particle" interaction and film separation from the wall. Prompt Atomization causes have also been detailed.

Support for disturbance creation due to all of the discussed mechanisms (liquid turbulence, hydrodynamic instabilities, gas-phase vortices and pressure fluctuations) exists. Of the suggested disturbance breakdown mechanisms only a few have corroborating experimental evidence in the film configuration—splashing due to droplet collision or ligament collapse^{59, 71}, bubbles rupturing⁶⁸, wave breaking⁵⁸, Rayleigh breakup²⁵, turbulence-induced separation²⁴ and bag breakup²⁷. Strong evidence of others, such as wave splitting^{18, 44}, ribbon formation⁵⁷, film separation⁷⁰ and stripping^{27, 62}, also exist. Perforation evolution and shattering remain in doubt as atomization routes for film disturbances. Prompt Atomization mechanisms are less well understood and no definitive proof exists that any one mechanism causes prompt atomization.

Vastly different operating conditions, disparities in emphasis and diverse figures of merit hamper the application of the existing understanding of atomization developed in other systems, primarily cooling tubes, to rocket injectors, however. These are the reasons that atomization mechanisms have been stressed over correlations. Different mechanisms may be important in different situations, but the understanding of the mechanism itself is applicable over a wide range of conditions. An examination of the mechanisms and an understanding of gas-centered swirl coaxial rocket injectors suggest that gas vortices and hydrodynamic instabilities may be important disturbance drivers with liquid turbulence, pressure fluctuations and perforation causes of lesser importance. However, doubt about the turbulence level of the swirling liquid may change the importance of liquid turbulence. Causes of disturbance breakdown are more difficult to determine, but wave splitting, bag breakup, stripping, shattering and Rayleigh breakup of ligaments remain strong candidates. If the film remains intact to the injector lip then film separation is expected to be important.

Still, one must remember that the breakdown of a disturbance only occurs if and when it reaches a critical size and remains at that size (or greater) for a sufficient time for the breakdown process to progress. Consequently, not all disturbed interfaces will undergo atomization, especially since the fluid spends a limited time within the atomizer. These limitations demonstrate the need to predict not only the mechanisms of disturbance initiation, growth and breakup, but the time and distances involved via predictions of growth rates, decay rates and critical sizes of disturbances and the time for breakdown of the disturbances as well. The current understanding of film atomization does not allow this amount of detail for most configurations, especially rocket injectors. Further experimental investigations are planned and will be needed to qualitatively and quantitatively describe atomization in gas-centered swirl coaxial atomizers.

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